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A life cycle co-benefits assessment of wind power in China

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A B S T R A C T

Wind power can help ensure regional energy security and also mitigate both global greenhouse gas and local air pollutant emissions, leading to co-benefits. With rapid installation of wind power equipment, it is critical to uncover the embodied emissions of greenhouse gas and air pollutants from wind power sector so that emission mitigation costs can be compared with a typical coal-fired power plant. In order to reach such a target, we conduct a life cycle analysis for wind power sector by using the Chinese inventory standards. Wind farms only release 1/40 of the total CO_2 emissions that would be produced by the coal power system for the same amount of power generation, which is equal to 97.48% of CO_2 emissions reduction. Comparing with coal power system, wind farms can also significantly reduce air pollutants (SO_2, NO_X and PM_{10}), leading to 80.38%, 57.31% and 30.91% of SO_2, NO_X and PM_{10} emissions reduction, respectively. By considering both recycling and disposal, wind power system could reduce 2.74×10^4 t of CO_2 emissions, 5.65×10^4 kg of NO_X emissions, 2.95×10^5 kg of SO_2 emissions and 7.97×10^4 kg of PM_{10} emissions throughout its life cycle. In terms of mitigation cost, a wind farm could benefit 37.14 US$ from mitigating 1ton of CO_2 emissions. The mitigation cost rates of air pollutants were 7.94 US$/kg of SO_2, 10.79 US$/kg of NO_x, and 80.79 US$/kg of PM_{10}.Our research results strongly support the development of wind power so that more environmental benefits can be gained. However, decentralized wind power developers should consider not only project locations close to the demand of electricity and wind resources, but also the convenient transportation for construction and recycling, while centralized wind power developers should focus on incorporating wind power into the grids in order to avoid wind power loss.

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1. Introduction

China's energy system relies heavily on fossil fuels. The total amount of energy consumption in 2012 reached 3.62 billion tons of standard coal in which the fossil fuels accounted for 90.61% [1]. Since 2010 China has overtook the United States and become the world's largest energy consumer [2], contributing to 21.92% of the global energy consumption in 2012 [3]. With its rapid industrialization process and urbanization, China's tremendous energy demand will continue to grow [4]. Moreover, China accounted for one-quarter of global carbon dioxide emissions in 2011 which mainly contributed by the fossil fuel consumption [5] and 80% of the world's rise in CO_2 emissions since 2008 [6]. In order to diversify the energy mix dominated by fossil fuels and fulfill the responsibility for global climate change mitigation[7], China's energy policy focuses on sustainable energy supply and reducing the overall intensity of carbon emissions by increasing the proportion of renewable energy use and reducing the fossil fuel consumption [8]. Chinese central government set up an ambitious target on increasing the proportion of non-fossil fuel energy sources so that such sources can account for 15% of the total primary energy consumption by 2020 [9], which indicates that 35% to 40% of the total electricity should be generated from renewable sources..

As one of the world's major renewable energy sources, wind power plays a key role in helping solve the energy supply problems in many countries [10,11]. Total electricity generation capacity to from wind power has grown rapidly from almost zero in 1980 to 197 gigawatts (GW) in 2011 globally [12], and the total installed capacity projected to reach 1150 GW by 2020 and more than 2500 GW by 2030, contributing to decarbonizetheglobal electricity supply [13]. Due to the fact that wind is one of the most abundant renewable energy resources in China, the National Energy Administration established in 2008 decided to develop wind power as one key measure for diversifying China's energy mix [14]. Since then, the installed capacity of wind power plants in China has experienced a fast growth. During the period of China's 11th five-year plan (2006–2010), the total installed capacity of wind power has reached 43.5 GW, accounting for 8.9% of China's the total new installed power capacity during that period, in comparison, the installed thermal power was 449 GW, accounting for 92% [15]. By the end of 2012, the cumulative installed capacity of wind power in China had reached 76 gigawatts (GW), the largest country in the world.

Coal-fired power plants are the main source of ambient air pollutants (including nitrogen oxides, sulfur oxides, dust, and other suspended particulate matter), leading to both global climate change and local air pollution [16,17]. Since wind power does not consume fossil fuels during its operation period and therefore does not emit greenhouse gas and air pollutants from its electricity generation [18,19], the application of wind power can achieve co-benefits, namely reducing both greenhouse gas and air pollutants [20]. The co-benefits effect has been discussed extensively in the international political arena such as in the United Nations Framework Convention on Climate Change [21], the United States Agencies [22], and Japanese Environment Strategies [23]. In general, co-benefits refer to the development and implementation of activities that simultaneously contribute to tackling climate change (such as reducing CO_2 emission) and solving local environmental problems (such as reducing the emissions of SO_2, NO_X and/or particulates) [24]. In the case of energy-related projects, strong linkages exist between global climate change and local environmental pollution [20]. For example, emissions from the combustion of fossil fuels contribute significantly to both global climate change and local environmental pollution, while developing renewable energy projects could have the co-benefits effect [25], approaches to mitigate global climate change can lead to less local environmental pollution or vice versa [26,27]. For instance, electricity production is responsible for a major portion of air pollution and carbon dioxide emission in USA, in which electric generation causes 64% of all emissions of sulfur dioxide, 40% of all man-made emissions of carbon dioxide and 26% of all emissions of nitrogen oxides [28].

Few studies have been carried out to investigate the contribution of wind powers to respond climate change and to reduce pollutants, but little attention has been paid to the overall performance of the whole life cycle of wind power plants. Yousuf and his colleagues calculated the greenhouse gas (GHG) contribution from grid connected power plants by employing the methodologies of Intergovernmental Panel on Climate Change (IPCC) and United Nations Framework Convention on Climate Change (UNFCCC), shows that the weighted average baseline emissions factor for wind power project in Pakistan is 0.606 t CO_2/MW h [29]. Another study chose Xinjiang of China as a case and found that during 2006–2010, emissions mitigation by wind power accounted for 4.88% (1.07×10^7 t) of carbon dioxide, and 4.31% (4.38×10^4 t) of sulfur dioxide, 8.23% (3.41×10^4 t) of nitrogen oxides, 4.23% (3.2×10^3 t) of $PM_{2.5}$ emission compared to emissions by the coal fired thermal power sector [20]. However, from the life cycle point of view, wind power plants have to consume resources including iron, steel, copper, fiberglass, epoxy, concrete, and other materials in the manufacturing and construction phase. Plus, all components have

to be delivered to the wind farms, inducing additional use of fossil fuels [30]. For instance, a study conducted in 2006 figured out that the carbon dioxide emissions of wind power ranged from 14 to 33 t per GW h of energy produced [31]. Another study conducted in 2008 by the Irish national grid found reductions in carbon dioxide emissions ranged from 0.33 to 0.59 t of carbon dioxide per MW h [28]. In addition, Environment Canada has estimated the average GHG intensity of electricity generation in Ontario and uncovered that the operation emissions of wind power is almost zero while the whole life cycle emission is 0.011 t CO_{2eq}/MW h [32].

However, similar studies have not been undertaken in China. Under such a circumstance, it is critical to fill such a research gap. Consequently, this paper aims to quantify the co-benefits performance of China's wind power system by comparing with coal-fired thermal power plants. The life cycle assessment approach will be employed in order to uncover co-benefits on responding global climate change and local air pollution. Other environmental impacts from wind power sector, such as noise, visual impacts and public health effect, will not be discussed in this study [33]

2. Methodology

According to Introduced by the life cycle assessment approach [34,35], firstly the system boundaries boundary of wind energy as well as and thermal power are first identified. Then, methodology on evaluating both environmental and economic benefits is presented so that co-benefits can be quantified followed by the introduction of the methodologies on environmental as well as economic impacts evaluation from the co-benefits perspective. Aims in order to comparing compare the overall performances between the wind energy system with and thermal power system, emissions and economic indicators are based on the single functional unit. For example, the generation of 1 kW h (kW h) of electricity is adapted as the functional unit in this study, and the corresponding amounts of CO_2 emissions and air pollutants (SO_2, NO_X and PM_{10}) per kW h of electricity are chosen as the indicators for environmental performances, and the monetary value (US$) of per kW h of electricity is chosen as the indicator for cost-effectiveness evaluation.

2.1. System boundary

System boundary determines the unit processes to be included in the life cycle assessment study. Defining system boundary is partly based on a subjective choice and can be decided during the scope phase [36]. The process flows for wind energy system and coal-fired thermal power system were are in Figs. 1 and 2, respectively.

2.1.1. System boundary definition for wind power system

In this study, the typical wind farm system in Yulin City of Guangxi of Zhuang Autonomous Region China was selected as a case study site. The developer, namely, China Huadian Corporation, is a state-owned enterprise and devotes to develop wind power by providing wind power equipment and related service in China [37]. This wind farm is equipped with 24 wind turbines, with a production capacity of 1.25 MW for each turbine, and *t* the operation life for each turbine is expected to be 20 years. The life cycle of one wind power systems can be divided into five stages, including (1) production, (2) transportation and installation, (3) power generation, (4) maintenance, and (5) end-of-life recycling and disposal. The input of non-renewable energy has been shown in each stage. In this study, raw material, fossil fuel consumption and corresponding emissions have been taken account of a life cycle process. Meanwhile, cost-effectiveness of a wind farm is considered because the cost plays a very important role in operating a wind farm [38]. Considering the data reliability and availability, the cost data of this wind farm was mainly extracted from a feasibility report of one wind farm (with a designed capacity of the 49.5 MW) in Kangping County of Liaoning province [39]. Uncertainties for such a life cycle assessment exist due to the incomplete inventory data [40], In order to address such an issue, a systemic aggregate uncertainty

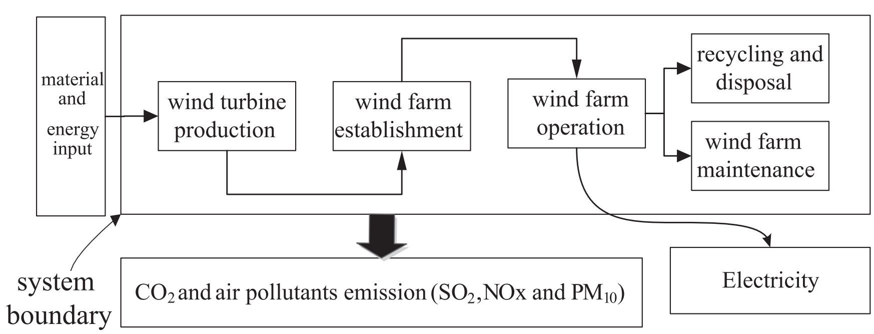

Fig. 1. System boundary of a wind power system.

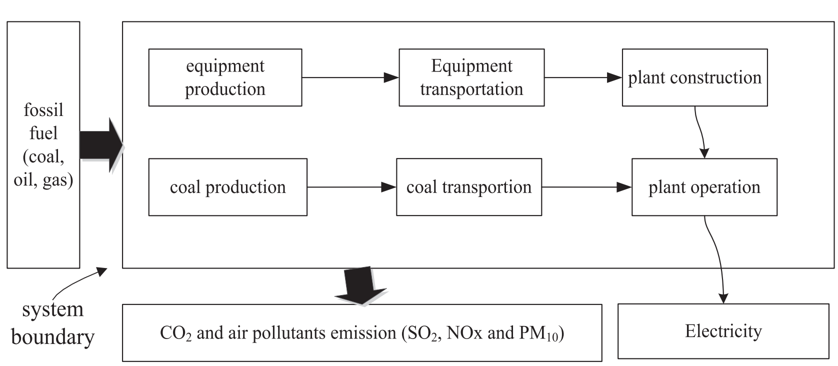

Fig. 2. System boundary of a coal-fired power system.

analysis is conducted by using a Monte Carlo calculation [41], so that rational conclusions can be made in Section 5.

For stage 1, namely, wind turbine production, environmental impacts of all raw materials are calculated based upon process unit in turbine production. Both upstream and downstream of material production are included in the inventory data. However, emissions from turbine manufacturing and assembling are ignored due to lack of reliable data. For stage 2, namely, wind farm establishment (including transportation and construction), all the turbine parts were delivered from manufacturers to the wind farm site. Transportation channels include railway, waterway and highway. The wind farm construction includes both tower foundation construction and substation construction, which consume a lot of concrete and steel materials. Emission data on concrete and steel production are extracted from relevant studies [41,42]. For stage 3, namely, wind farm operation (power generation), wind power production emits almost zero emissions. Also, emissions from power transmission and distribution are quite marginal and can be ignored. For stage 4, namely, maintenance and operation, one wind farm has to be regularly maintained so that it can be functionally operated. Usually, the most important maintenance is to replace the blade during its life cycle, thus, related data are extracted from a relevant study for our analysis [43,44]. In addition, considering that the wind farm consumes 6% of the electricity generation, therefore we subtracted the auxiliary power consumption from the gross generation. For stage 5, namely, end-of-life recycling and disposal, recycling of main parts from one turbine is considered since such an approach can avoid the consumption of virgin materials, which is more energy intensive, so that both energy consumption and environmental emissions can be reduced. However, since the Yunlin wind farm does not have any detailed data in this regard, we had to use the relevant data from a previous study [45]. The related recycling and disposal data are listed in Table 1.

Table 1
Material types and disposal methods considered [45].

Material types	Disposal methods
Iron	Recycling (10% losses)
Fiberglass	Landfill (100%)
Epoxy	Landfill (100%)
Concrete	Landfill (100%)
Steel	Recycling (10% losses)
Copper	Recycling (5% losses)

2.1.2. System boundary definition for one coal-fired power system

The life cycle of a coal-fired power system includes six stages, namely (1) equipment production, (2) equipment transportation, (3) plant construction, (4) coal production, (5) coal transportation, and (6) plant operation. The life cycle emissions of a 600 MW thermal power plant are mainly referred from the literature [46]. The efficiency rate of coal consumption is set up as 3.12 kW h/kg and the operation hours are usually defined as 5000 h per year with a service life of 30 years. The conversion factor of TSP to PM_{10} is 0.54 [47]. Table 2 lists all the detailed data.

Table 2
Life cycle emissions of 1 kW h electricity produced by a 600 MW coal-fired plant (kg/kW h) [46,47].

Process	GHG (CO_2 equivalent)	SO_2	NO_x	TSP
Coal production	9.888E−02	2.688E−05	1.613E−05	2.285E−05
Coal Transportation	1.890E−02	6.310E−05	1.771E−04	1.217E−05
Equipment Production	4.136E−04	1.093E−06	5.636E−07	4.884E−07
Equipment Transportation	1.537E−05	5.132E−08	1.440E−07	9.897E−09
Plant construction	9.143E−04	1.335E−06	2.413E−06	4.801E−06
Plant operation	9.049E−01	5.000E−04	6.000E−04	1.500E−04
Total	1.024E+00	5.925E−04	7.963E−04	1.903E−04

2.2. Environmental impacts

In order to compare the environmental impacts between one wind power system and one coal-fired thermal power system, GHGs (CO_2 equivalent) and air pollutants emissions (SO_2, NO_X, PM_{10}) from the whole life cycle are considered. Most modern wind turbines employ similar technologies, which makes it relatively easy for such a comparison [48]. However, material processing technologies for turbine manufacturing are country-specific [49]. Here we employ the Chinese data on raw material production for turbine manufacturing so that more accurate results can be obtained.

2.3. Economic impacts

Economic cost is a key factor so that one proposed project can be determined for real implementation. The economic information and data were taken from the feasibility report of a 49.5 MW wind farm in Kangping County, Liaoning Province, China duo to the lack of data from Yulin wind farm. The total investment of this project was 73.59 million (US$) and the annual grid electricity is 11.04×10^4 MW h. In addition, the annual revenue is 7.54 million (US$). The economic data for this wind power project is shown in Table 3.

The coal-based comparative annual cost was firstly estimated in this study. In this research, the wind farm was not considered as a single project, but a comparative case to a coal-fired thermal plant, thus, the comparison-based net annual cost (G_{CNAC}) was employed and defined as the sum of the equivalent annual project cost (Y_{EAPC}) plus the annual fuel cost saving (Y_{AFCS}) plus annual on-grid energy sale revenue (Y_{ASR}) (Eq. (1)) [20]. This equation indicates that, comparing to a coal-fired thermal plant, the economic capitalized cost for a wind farm project should include the potential savings from the avoidance of fossil fuel consumption and the on-grid electricity sales revenue. These two aspects are also the linkage determinants for measuring co-benefits in the following sections of this paper.

$$G_{CNAC} = Y_{EAPC} + Y_{AFCS} + Y_{ASR} \tag{1}$$

The equivalent annual project cost (Y_{EAPC}) is defined as the sum of equivalent annual value (C_{EAV}) and annual maintenance cost (C_{AMC}) (Eq. (2)), the annual maintenance cost include the average annual operating cost, average annual income tax, and average annual additional sale tax. The equivalent annual value (C_{EAV}) was converted from the total investment based on the discount rate (r) and service life time (n), see Eq. (3) [49,50].

$$Y_{EAPC} = C_{EAV} + C_{AMC} \tag{2}$$

$$C_{EAV} = \frac{C_{Total} \times r}{1-(1+r)^{-n}} \tag{3}$$

where, C_{Total} is the project's total investment; C_{AMC} is the annual maintenance cost; r is the discount rate (0.05); n is the service life.

The annual fossil fuel cost saving (Y_{AFCS}) is defined as the total amount of annual energy saving (G_{AES}) times unit energy price (P_E), shown in Eq. (4). In this study, the total amount of annual energy saving is defined as the annual coal saving since cola is the main

energy source for China's power generation [20], and the coal price was estimated at 95.24 US$/ton, which was the average price in 2012 [1]. The amount of annual energy saving (G_{AES}) from one wind farm was converted to the total coal consumption in a coal-fired plant which produce the equivalent final consumption-side electricity (E_{AEQ}), Eq. (5) shows the G_{AES} calculation process, in which, R denotes the rate of unit coal consumption for unit electricity generation. In China, such a rate (R) is estimated at 466 g/kW h according to a report on coal-fired thermal power [51].

$$Y_{AFCS} = G_{AES} \times P_E \tag{4}$$

$$G_{AES} = \mathrm{E}_{AEQ} \times \mathrm{R} \tag{5}$$

The annual revenue from on-grid electricity sale (Y_{ASR}) is defined as the grid electricity generation amount ($E_{on\text{-}grid}$) times unit electricity price (P_{grid}), Table 3 lists all the related parameters, while the Eq. (6) shows how to calculate such revenue.

$$Y_{ASR} = E_{on-grid} \times P_{grid} \tag{6}$$

Cost-effectiveness is a key part of economic analysis so that costs from different engineering choices can be compared in order to find the cheapest solution [52]. In this study, the indicator on cost-effectiveness is a ratio of emissions reduction to economic cost of one wind power project. Such a ratio (R_{CE}) can be calculated by dividing the comparison-based net annual cost (Y_{CNAC}) by annual equipment reducing amount of element i (R_i, element i indicates air pollutant or CO_2), listed in Eq. (7). During the operation period of one wind power plant, it is clear that the corresponding electricity production generates almost zero air pollutants and CO_2 emissions and can significantly reduce the overall environmental emissions, comparing with one coal fired power plant with the same production capacity.

$$R^i_{CE} = Y_{CNAC}/R^i_{AER} \tag{7}$$

where, R_{CE} denotes the cost-effectiveness ratio. One positive value of R_{CE} indicates that this project will bring additional financial burden to the investors, while a negative value indicates that the investors will receive economic benefit from such a project. R_{AER} denotes the net annual reduction amount of element i (air pollutants or CO_2), which equals to the annual reduction amount of element i in operation period (P_{AEP}) minus the average annual releasing-emission amount of element i in the whole life cycle process (excluding recycling and disposal) (R_{LCA}). Eq. (8) shows its calculation process.

$$R^i_{AER} = R^i_{AEP} - R^i_{LCA} \tag{8}$$

3. Inventory assessment

Material and related emission data for the whole life cycle are inventoried in order to assess the performance of one wind power system.

3.1. Material inventory data

In terms of the selected case in Yulin City, Guangxi of China, the annual total output of this wind farm per year is 2.72E+06 kW h with total 2180 operation h per year. The hub height of each wind turbine is 68 m and the diameter of each blade is 64 m. A 35 kW box-type transformer connects all wind turbine towers. This wind farm is also equipped with a substation (with an 110 kV step-up transformer) in order to decrease the line-loss of electricity. All control units are installed in the substation. Life cycle assessment on one wind farm covers six parts: (1) wind turbine (rotors, nacelle, tower, and other components); (2) substation (transformers and control units); (3) delivery of equipment and other materials; (4) installation (tower foundation, substation foundation, etc.); (5) operation and maintenance; and (6) end-of-life recycling and disposal [53] (Table 4).

3.2. Embodied emission for different materials

Emissions factors for all the required raw materials' production, recycling and disposal are considered.

3.2.1. Fiber glass and epoxy resin production

It is very important to understand the boundary of the material life cycle. For the glass fiber reinforced pallet, the following processes are included in the system, production of glass fiber, polypropylene production, pallet production, use (including transporting) and disposal of the pallets [54,55]. The aggregated emission factors were as follows (Tables 5, 6):

3.2.2. Silica production

Industrial silicon is essential to businesses such as metals industry, semiconductor grade silicon manufacturing and others. A life cycle assessment on industrial silicon manufacturing process is crucial to calculate related energy-saving and pollutants mitigation. Reliable data on silica production are not directly available in this study. Thus, we used the data from a previous relevant study [46]. The aggregated emissions factors of industrial silicon from silicon ore are listed in Table 7.

3.2.3. Copper production

In China copper is mainly manufactured through pyrometallurgical processes. Life cycle analysis for copper includes mining, ore dressing, accessory material mining and dressing, comminution, smelting (matte smelting, bessemerize), electrorefining, reverberatory-refining, remelt ingot, accessory material smelting and slag cleaning [56]. The aggregated emissions factors of related pollutants from copper production are listed in Table 8. Unfortunately, emission rate of PM_{10} from copper production is not available.

3.2.4. Steel production

The process of steel production contained iron ore mining and transportation, ore dressing, comminution and transportation, iron ore sintering, blast furnace iron making, steelmaking, steel

Table 3
Wind power project economic data.

Economic data			
Total investment	73.59 million US$	Service life	20 years
Annual on-grid energy quantity	11.040×10^4MWh	Average annual operating cost	7.19 million US$
Annual on-grid energy sale revenue	7.54 million US$	On-grid energy price (excluding tax)	0.07 US$/kW h
Average annual income tax	0.43 million US$	Average annual additional sale tax	0.05 million US$

rolling (roughing roll) [57]. The aggregated emissions data are listed in Table 9.

3.2.5. Cement production

The process of cement production focuses on the raw material mining, processing, and fuel acquisition, sintering, and cement production [42,58]. Aggregated emissions factors are listed in Table 10.

Table 4
Components of a wind farm.

Item	Materials	Quantity (t)	Unit
Wind turbines			
Rotors	Resin	1.54E+02	t
	Fiber glass	1.06E+02	t
	Cast iron	1.9E+02	t
Nacelle	Iron	4.8E+02	t
	Steel	5.6E+02	t
	Silica	9.6E+00	t
	Copper	9.1E+01	t
	Fiber glass	9.00E−01	t
	Resin	1.30E+00	t
Tower	Steel	2.1E+03	t
Substation			
Transformer	Silica	6.0E−01	t
	Steel	1.1E+01	t
	Copper	4.8E+00	t
Computers		5.0E+00	
Building works			
Tower foundations	Concrete	8.3E+03	t
Substation foundation	Steel bar	9.9E+02	t
	Concrete	1.6E+02	t
	Steel bar	7.9E+00	t
Operation and maintenance			
Blades	Resin	5.21E+01	t
	Fiber glass	3.59E+01	t
Generators	Silica	7.2E−01	t
	Copper	7.9E+00	t
	Steel	1.7E+01	t

Table 5
Aggregated emissions factors of pollutants for the glass fiber pallets [54,55].

Pollutants	Emission factors	Unit
CO_2	4.87E+00	kg/kg
NO_X	3.42E+01	g/kg
SO_2	1.93E+01	g/kg
PM_{10}	3.83E+00	g/kg

Table 6
Aggregated emissions factors of pollutants for the epoxy resin [54,55].

Pollutants	Emission factors	Unit
CO_2	3.94E+00	kg/kg
NO_X	1.47E+01	g/kg
SO_2	2.29E+01	g/kg
PM_{10}	Not available	g/kg

Table 7
Emission factors for industrial silicon from silicon ore (kg/kg) [46].

Pollutants	Emission factors	Unit
CO_2	9.04E−01	kg/kg
NO_X	5.00E−04	kg/kg
SO_2	6.00E−04	kg/kg
PM_{10}	8.40E−05	kg/kg

3.2.6. Iron production

Related iron production data were obtained from literatures [41,59]. Table 11 lists the related aggregated emissions factors for iron production.

3.3. Transportation data

Through our investigation in this case wind farm, we found that the average delivery distance is around 1000 km (railway takes 600 km, waterway 300 km and highway 100 km) [60]. The energy consumption rates and equations of one electric locomotive and one coal ship are listed in Table 12.

3.3.1. Electric locomotive

Due to the fact that coal-fired power plants accounted for 75% of China's total electricity generation in 2012 [1], we assumed that the electric locomotive consumed electricity from coal-fired plant.

The equationto calculate CO_2 and air pollutants emissions from fossil fuel combustion were shown in formula (9), where E_{ij} is the emission of air pollutant i from fuel j, EF_{ij} is the emission factor for air pollutant i and fuel j, and F_j is the consumption amount of fuel j (Table 13).

$$E_{ij} = EF_{ij} \times F_j \tag{9}$$

3.3.2. Diesel trucks

In this study, we took diesel trucks as delivery vehicles. The emission factors of diesel truck were from a reference based on calculation by the COPERT model in China [61] (Table 14).

3.3.3. Coal ship

The waterway transportation by coal ships is considered in this study. The emission factors were based on the coal combustion (Table 15) [62,63].

Table 8
Aggregated emissions from production of one ton copper.

Pollutants	Emission factors	Unit
CO_2	1.91E+03	kg/t
NO_X	1.35E+05	kg/t
SO_2	1.35E+05	kg/t
PM_{10}	Not available	kg/t

Table 9
Aggregated emissions factors from production of 1 kg steel in China.

Pollutants	Emission factors	Unit
CO_2	7.57E+00	kg/kg
NO_X	1.54E+01	g/kg
SO_2	5.04E+01	g/kg
PM_{10}	2.40E+01	g/kg

Table 10
Aggregated emissions factors from production of 1 ton steel.

Pollutants	Emission factors	Unit
CO_2	1.28E+00	t/t
NO_X	2.81E+00	kg/t
SO_2	2.31E+00	kg/t
PM_{10}	3.17E+00	kg/t

Table 11
Aggregated emissions factors from production of one ton iron.

Pollutants	Emission factors	Unit
CO_2	7.88E−01	t/t
NO_X	5.62E−02	kg/t
SO_2	4.41E−02	kg/t
PM_{10}	3.54E−01	kg/t

Table 12
Energy consumption rate of for one electric locomotive and one coal ship.

Transport	Energy consumption rate	Unit
Electric locomotive	108	kW h/(100,000t km)
Coal ship	12	kg/(1000 t km)

Table 13
Direct emission factors of coal-fired power plants.

Pollutants	Emission factors	Unit	References
CO_2	1.97E+00	t/t	[62]
NO_X	6.58E−03	t/t	[63]
SO_2	8.46E−03	t/t	[63]
PM_{10}	8.70E−04	t/t	[63]

Table 14
Emission factors of diesel trucks.

Pollutants	Emission factors	Unit
CO_2	1612	g/km
NO_X	14.3	g/km
SO_2	0.5	g/km
PM_{10}	0.5	g/km

Table 15
Emission factors of coal ships.

Pollutants	Emission factors	Unit
CO_2	1.9745	t/t
NO_X	4	kg/t
SO_2	10	kg/t
PM_{10}	1.6	kg/t

4. Results

4.1. Environmental impacts

Environmental impacts in this study include CO_2 and main air pollutants (SO_2, NO_X and PM_{10}) emissions. In order to provide a complete picture on wind power system's environmental performance, a life cycle assessment that includes material emission data was conducted. The results indicate that significant environmental benefits can be obtained, comparing with one coal fired power system with the same power production capacity. Fig. 3 shows the detailed comparison results for the two systems, in which it is clear that this wind farm only released 1/40 of the total CO_2 emission that would be produced by the coal fired power system, equal to a CO_2 emission reduction of 97.48%. Fig. 4 shows that this wind farm releases much less air pollutants (SO_2, NO_X and PM_{10}) than those from the coal fired power system. The corresponding ratios for SO_2, NO_X and PM_{10}between the wind power system and the coal fired power system are10/51, 35/82 and 38/55, equal to 80.38%, 57.31% and 30.91% of SO_2, NO_X and PM_{10} reduction, respectively. If we consider end-of-life recycling and disposal of the wind power system, it could additionally reduce 2.74E+04 t of CO_2 emission, 5.65E+04 kg of NO_X emission, 2.95E+05 kg of SO_2 emission and 7.97E+04 kg of PM_{10} emission (Fig. 5).

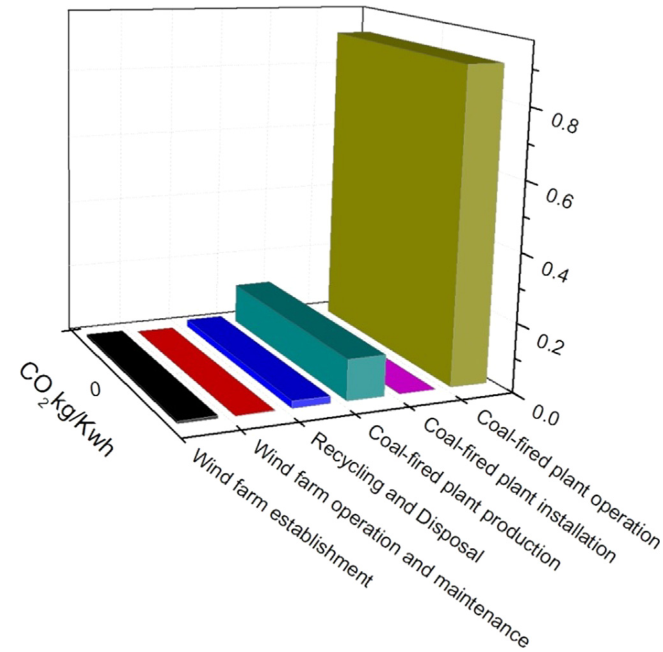

Fig. 3. Comparison of CO_2emissions for each unit process of the wind power system and coal-fired power system.

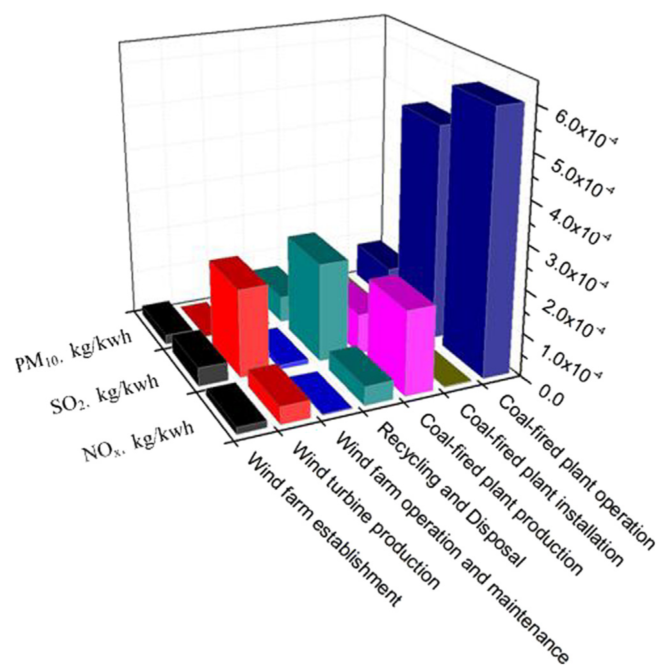

Fig. 4. Comparison of air pollutants emissions for each unit process.

4.2. Economic analysis

Although it is clear that the application of wind power can significantly reduce both CO_2 and air pollutant emissions, in reality, the coal-fired power system is still dominated in China due to relatively cheaper coal price and rich reserves.

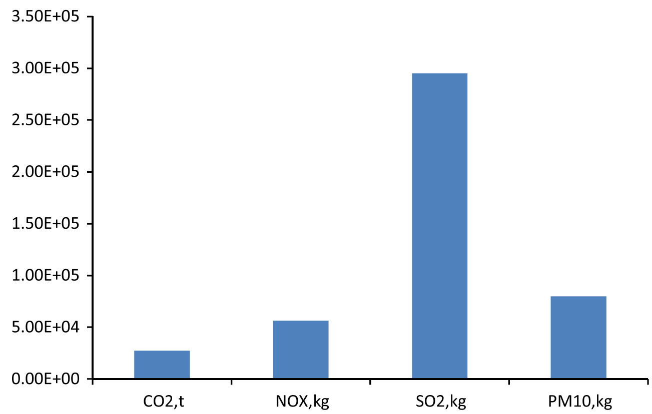

Fig. 5. Additional emission reduction from end-of-life recycling and disposal for one wind power system.

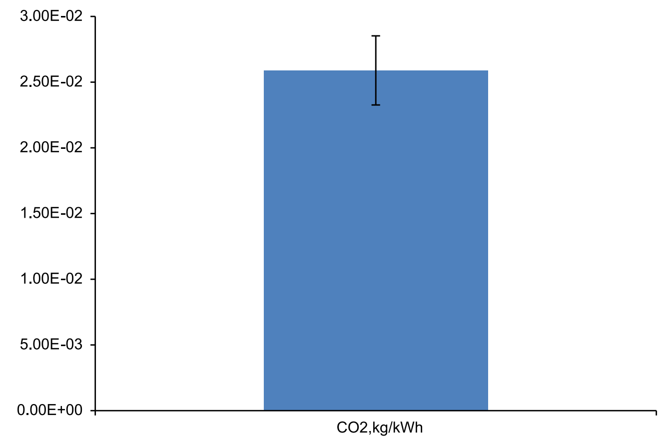

Fig. 6. Environmental impacts from configurations under 95% confidence range uncertainties.

Table 16
Cost-effectiveness effectiveness data for one wind farm.

CO_2, US$/t	SO_2, US$/kg	NO_X, US$/kg	PM_{10}, US$/kg
−37.14	−7.94	−10.79	−80.79

Table 17
Uncertainties for unit processes of all turbine configurations.

Unit process	Turbine production	Building works	Operation and maintenance
This study	23.34%	24.49%	23.43%

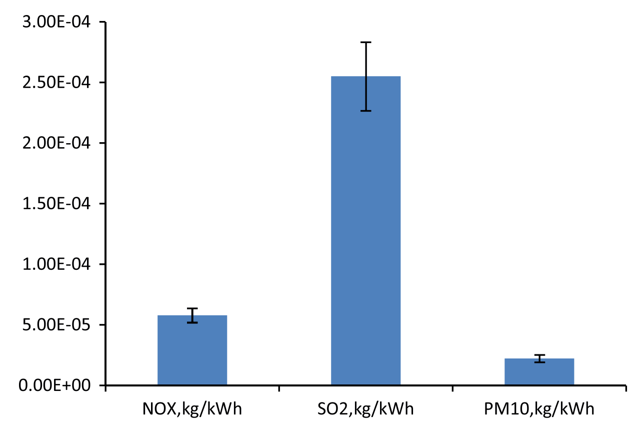

Fig. 7. Environmental impacts from configurations under 95% confidence range uncertainties.

Consequently, it is necessary to carry out an economic analysis on such a wind farm project so that cost-effectiveness of one wind power system can be identified. Table 16 shows our research findings on economic benefits for one unit CO_2 and air pollutants emissions mitigation.

5. Uncertainty analysis

In order to improve the reliability of this life cycle assessment, it is critical to conduct an uncertainty analysis. A data quality matrix was established so that all inventory data are included for quantifying the associated uncertainty. Table 17 lists the uncovered uncertainties for different unit processes. A Monte Carlo simulation was undertaken in order to detail the results of life cycle assessment by a probable range of values in according with different unit processes (Figs. 6 and 7). From policy implication point of view, we suggest that decentralized wind power developers should consider the appropriate location for such a project so that it can close to both energy demand users and service providers, while those centralized wind power developers should consider the linkages of their wind power to the national grid so that power loss can be reduced or avoided. In addition, appropriate site selection for such a project also need to consider the final recycling and disposal of their wind power equipment after the end of their life cycles so that all the valuable components and materials can be reused or recycled.

6. Conclusions

The increasing concerns on global climate change and local air pollution require more application of renewable energy sources, such as solar power and wind power. However, quantified information on encouraging the development of renewable energy systems is still lacking. Under such a circumstance, in order to compare co-benefits between one wind power system and one coal fired power system with the same power production capacity, a life cycle approach is employed in this study. In addition, cost-effectiveness for one wind power system was uncovered so that decision makers can see the potential economic benefits from such a mitigation effort. In general, research findings from this study can contribute to the application of renewable energy sources so that more resources will be allocated to support the rapid development of such sectors. Particularly, with the effective enforcement of increasingly strict air pollution policies and increasing pressures on responding climate change, traditional fossil fuel based energy supply enterprises will face more pressures on reducing their environmental emissions and higher costs. Consequently, it is timely for such enterprises to pay more attentions on facilitating the employment of appropriate renewable energy technologies and equipment.

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